SKA CD-EOR Science Team Meeting 2024

Extracting the HI 21 cm signal from the ground-based observation using Artificial Neural Networks

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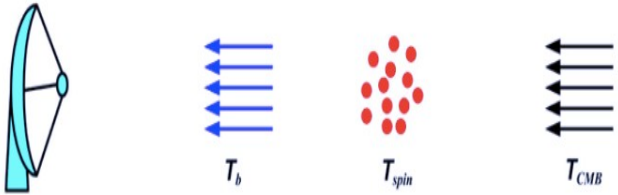
Credits : SKAO

Observation of 21-cm Signal

$$\delta T_b(\nu) = \frac{T_s - T_\gamma}{1+z}(1 - \exp^{-\tau_{\nu_0}})$$

$$\delta T_b \approx 27(1-x_i)\left(\frac{\Omega_{b,0}h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{m,0}h^2}\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_\gamma}{T_s}\right)$$



Field 1959; Pritchard & Loeb 2012

Observing type: Single radiometer

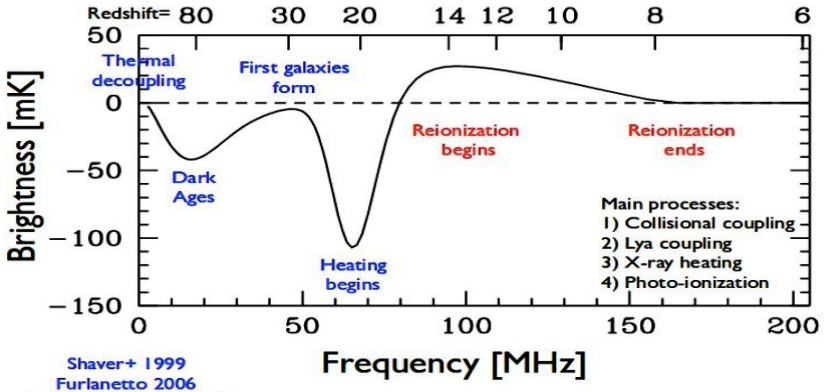
Signal: Global 21-cm Signal

Experiments: EDGES, SARAS, BigHorns, LEDA, REACH

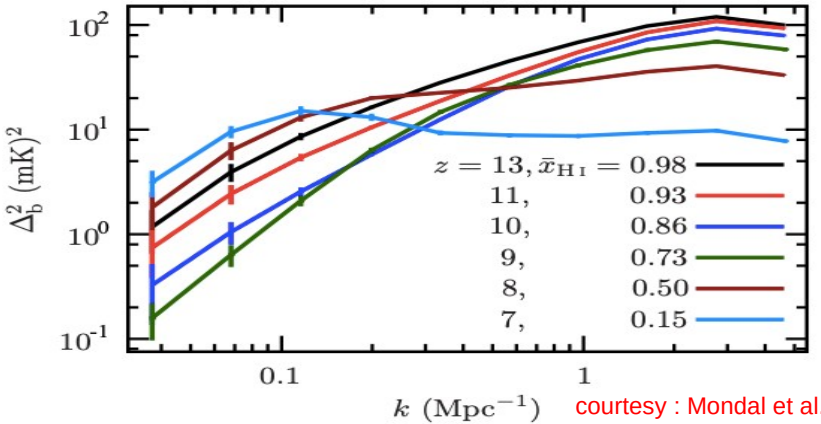
Observing type: Radio Interferometers

Signal : HI 21cm Power Spectrum, Tomography of IGM

Experiments : LOFAR, GMRT, HERA, MWA, SKA



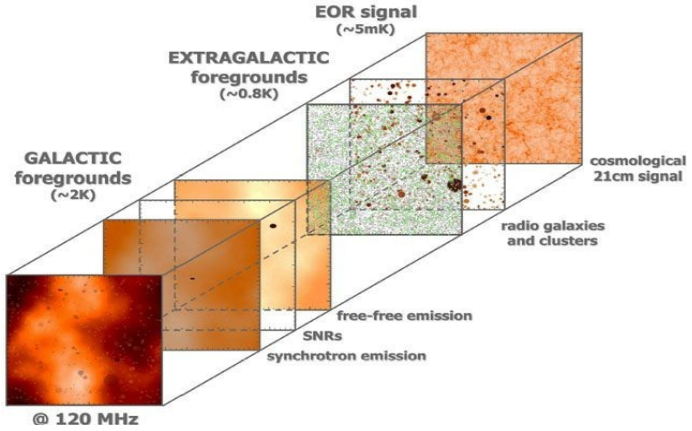
Shaver+ 1999
Furlanetto 2006
Pritchard & Loeb 2010



courtesy : Mondal et al. 2015

21CM Cosmology: Observational Challenges

- **Galactic and Extragalactic Foreground**



- **Earth's Ionosphere**

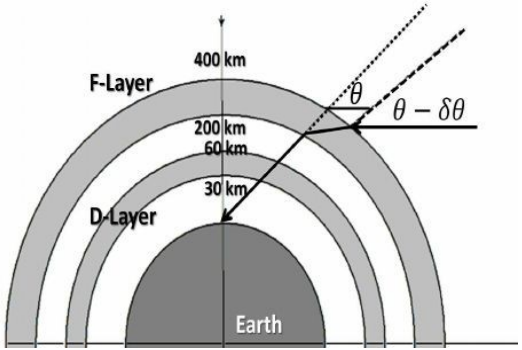


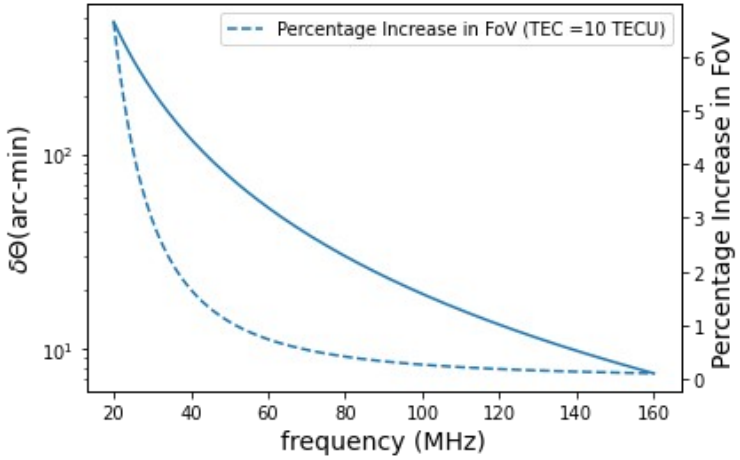
Fig : Schematic representation of the ionosphere showing the F- and D- layers (not scaled), which show the refraction. (Datta et al. 2016)

- **Radio Frequency Interference (RFI)**
- **Other Systematics effects**

In **E. Shen et al. 2022**, it is demonstrated that, under turbulent ionospheric conditions, an error exceeding 5 % in our understanding of the ionospheric parameters could result in false or null detection.

21CM GLOBAL SIGNAL: Effect of Ionosphere

Ionospheric Refraction due to F-layer

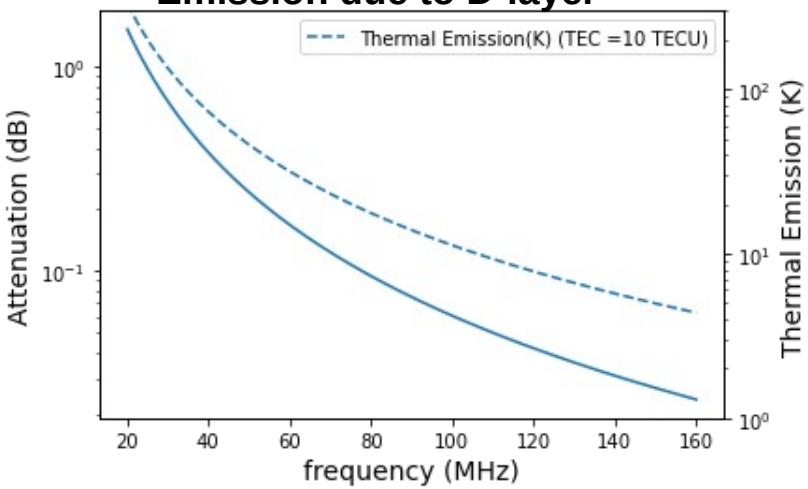


Increase in the effective FoV

$$T_{\rm sky}^{\rm iono}(\nu,\, t;\, \Theta_0,\, \Phi_0) = \int_0^{2\pi} d\Phi \times \int_0^{\pi/2} d\Theta B'(\nu,\, \Theta - \Theta_0 - \delta\theta(t),\, \Phi) \times T_{\rm sky}(\nu,\, \Theta - \Theta_0,\, \Phi - \Phi_0)\sin\Theta$$

Signal (T_{21}) + Foreground (T_{FG})

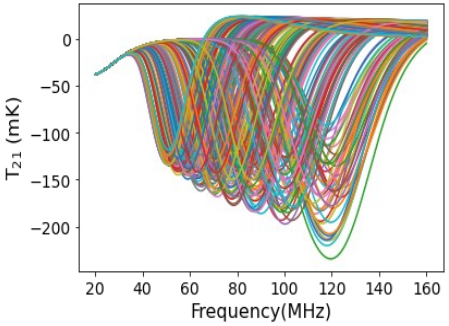
Ionospheric Absorption and Thermal Emission due to D-layer



$$T_{Ant}^{iono}(\nu, TEC(t), \Theta_0, \Phi_0) = T_{sky}^{iono}(\nu, t; \Theta_0, \Phi_0) \times (1 - \tau(\nu, TEC(t)) + \tau(\nu, TEC(t)) * < T_e >$$

(Tripathi A. et al. 2024, MNRAS)

Training Data Sets

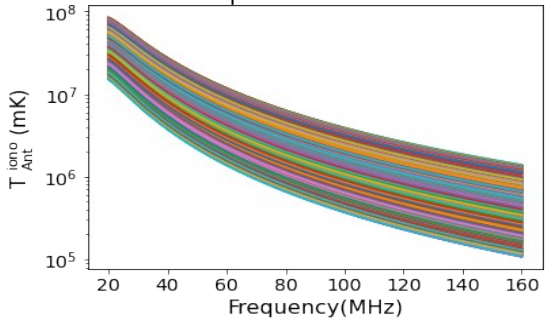


+

3rd order log(T)- log(ν0) polynomial model

Foreground + Ionospheric effects

We use the Accelerated Reionization Era Simulations (ARES) code was designed to rapidly generate models for the global 21- cm signal. (Mirocha et al, 2012, 2015).



Training Parameters
21-cm Global Signal :- Jref, Jz0, Xz0, Tz0 Jdz, Xdz,Tdz (**Harker et al. 2016b**). Each parameters varies by ±50 %.
Foreground :- a0, a1, a2, a3 (**Harker (2015)**)
Ionosphere :- TEC=10 TECU, Te= 800 K
Each Ionospheric parameters varies by ±1%.

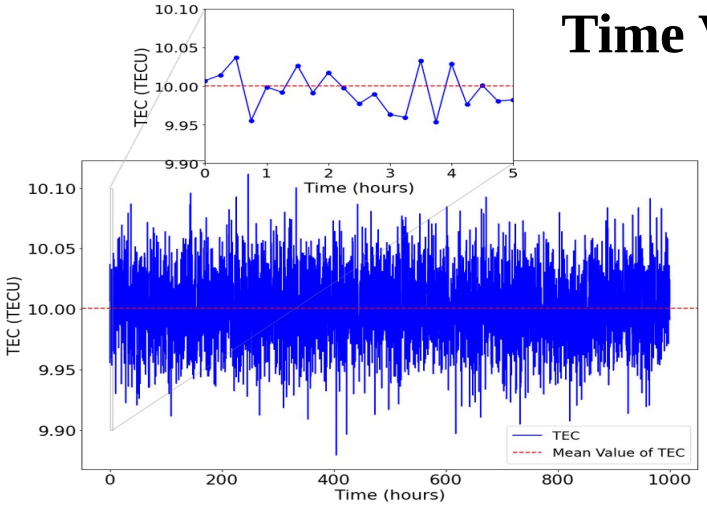
(Tripathi A. et al. 2024, MNRAS)

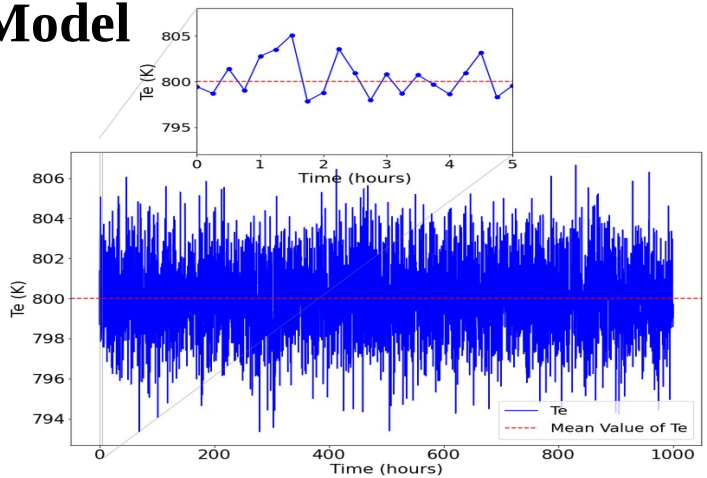
Parameters	R2 Score	RMSE
J_{ref}	0.9614	0.0628
J_{z0}	0.9738	0.0605
X_{z0}	0.9713	0.0616
T_{z0}	0.9668	0.0577
J_{dz}	0.9634	0.0608
X_{dz}	0.9578	0.0658
T_{dz}	0.9595	0.0636
a_0	0.9810	0.0439
a_1	0.9655	0.0590
a_2	0.9586	0.0642
a_3	0.9610	0.0625
TEC	0.9658	0.0578
T_e	0.9728	0.0588

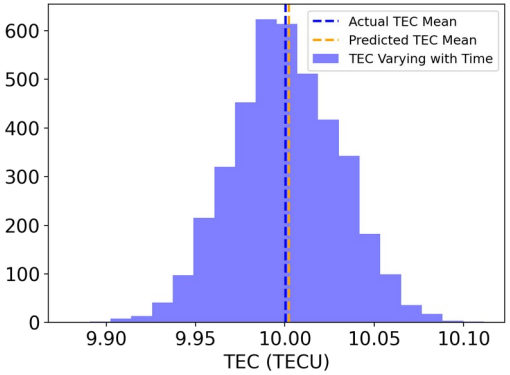
ANN Model → **Saved ANN Model**

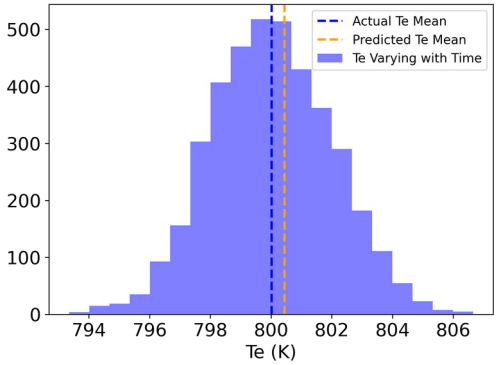
Test Data set (Signal + Foreground + Ionospheric effect + Thermal Noise)

Time Varying Ionosphere Model







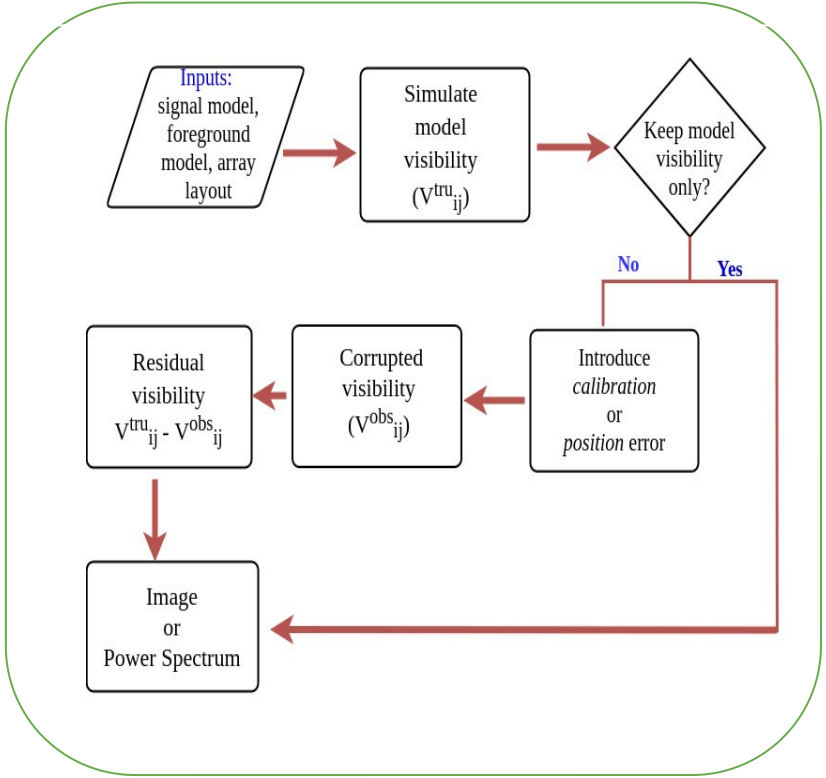


Conclusion: Simple ANN is robust in 21cm signal parameter estimates in presence of slowly varying ionosphere.

Tripathi A. et al. 2024, MNRAS

Flowchart: Observational Pipeline - 21cmE2E

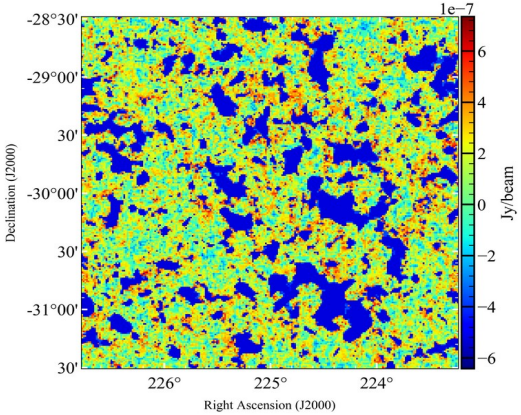
- In A. Mazumder et al. 2022, they have developed the 21cmE2E pipeline to simulate interferometric observation.



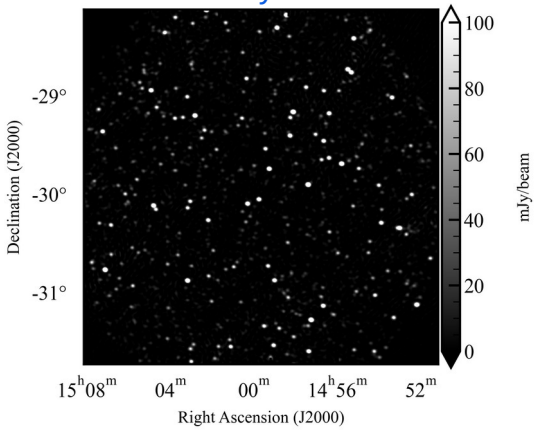
(A Mazumder et al. 2022)

Simulation inputs for the Synthetic Observation

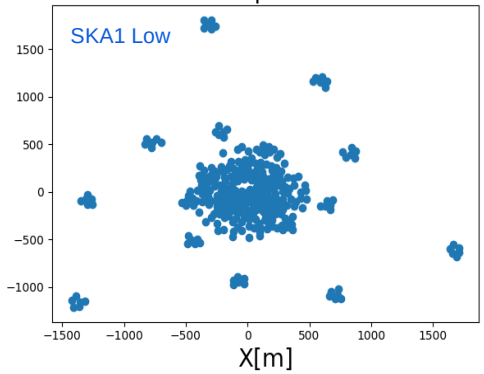
21cm Signal



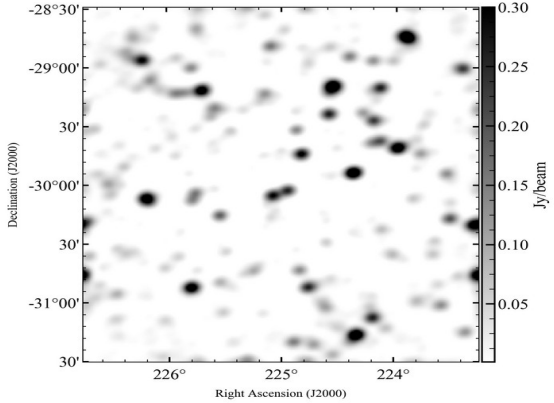
Global sky model



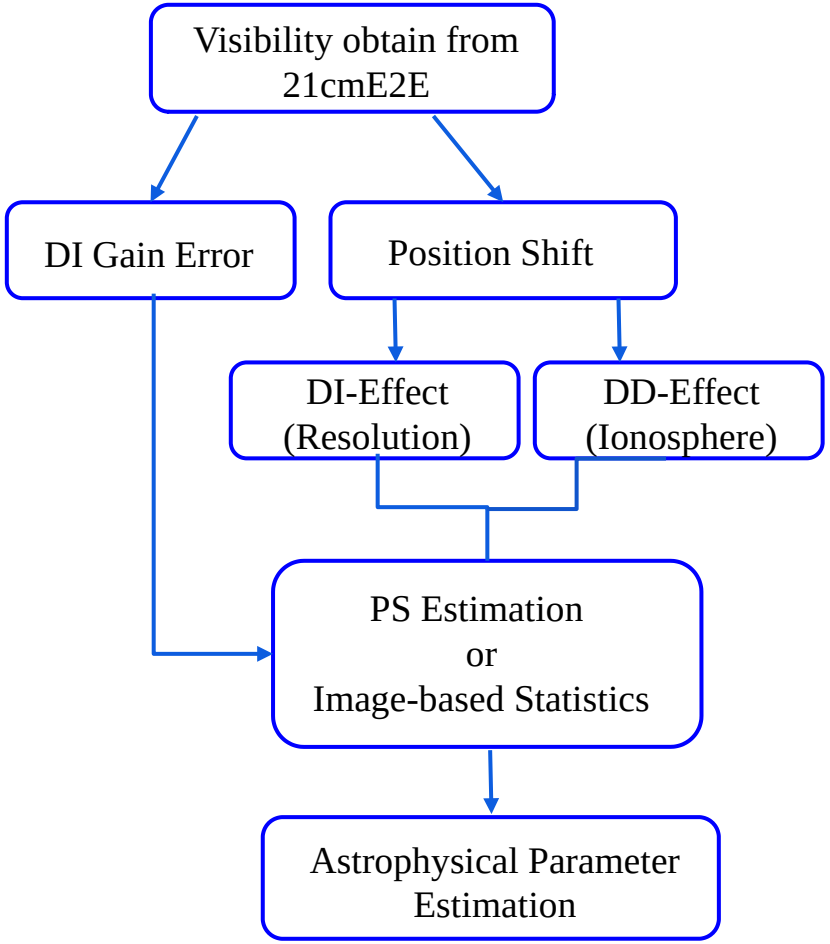
Telescope Model



Parameter	Value
Central Frequency	142 MHz (z~9)
Bandwidth	8 MHz
Number of frequency channels	64
Field of view	4°
Number of array elements:	
SKA1-Low Core	296
Maximum baseline (m):	2000
Synthesised beam (arcmin):	2.5

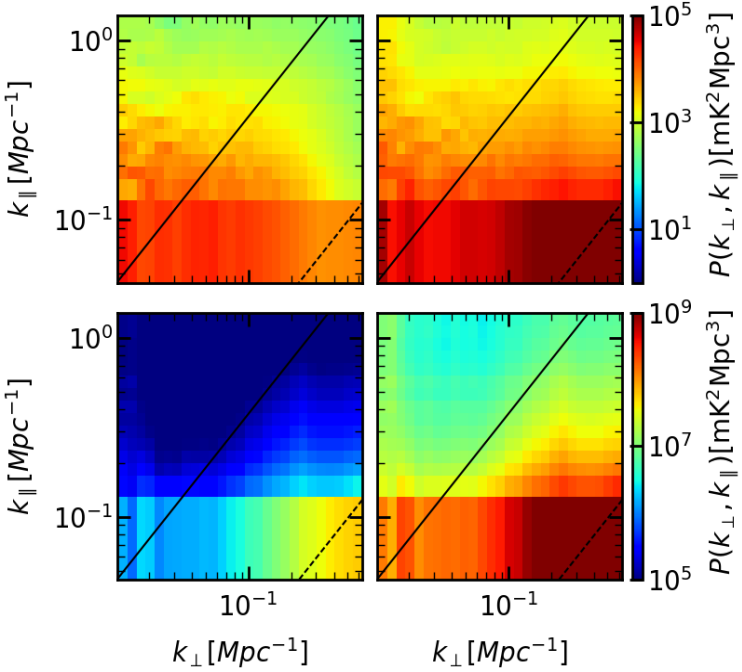


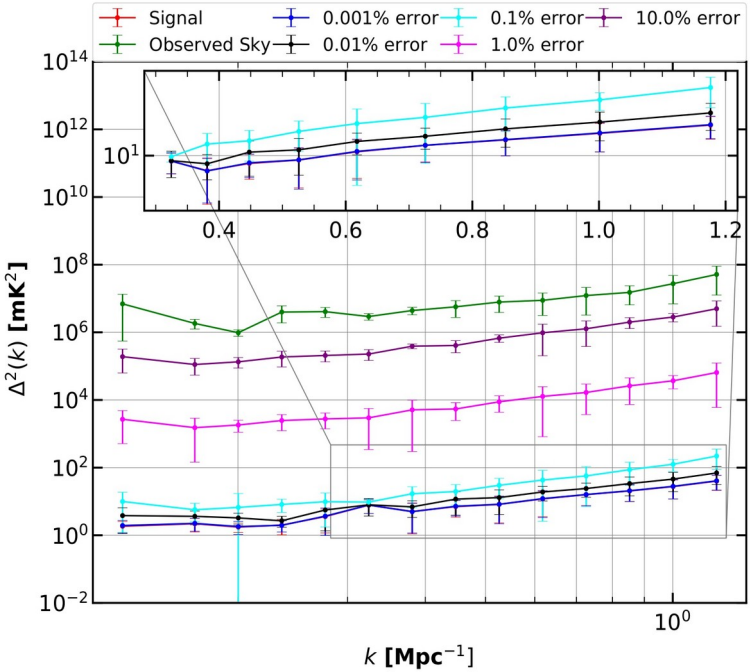
Utility of this Observation Pipeline for Various Scientific Case Studies



Power Spectrum Estimation : Gain Calibration Error

- Power spectrum analysis - Spherical averaged PS follows signal power if residual calibration error is > 0.1% is exceeds signal power significantly for greater error

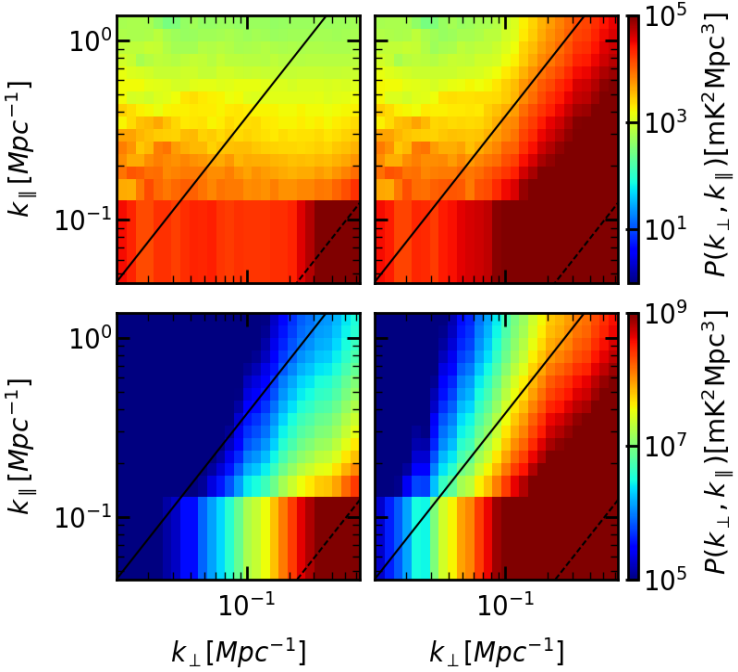


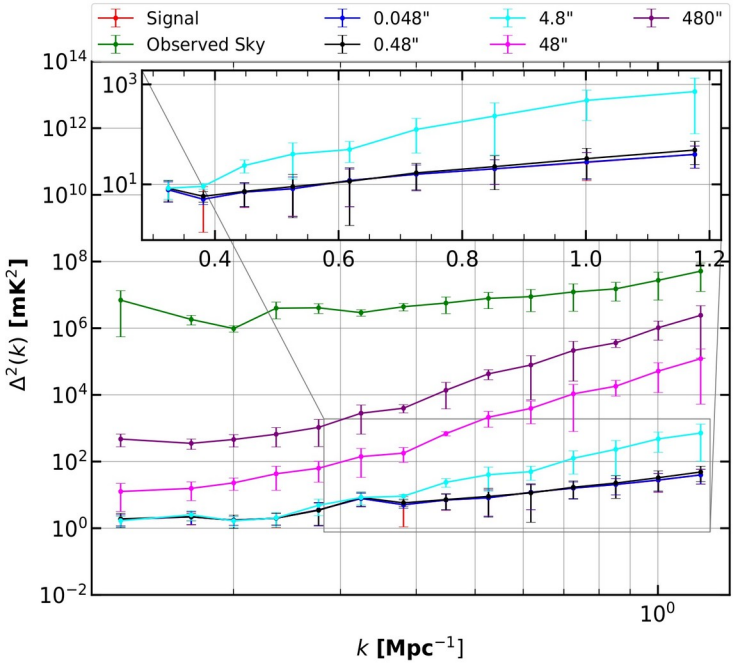


Mazumder et al. 2022

Power Spectrum Estimation : Position error

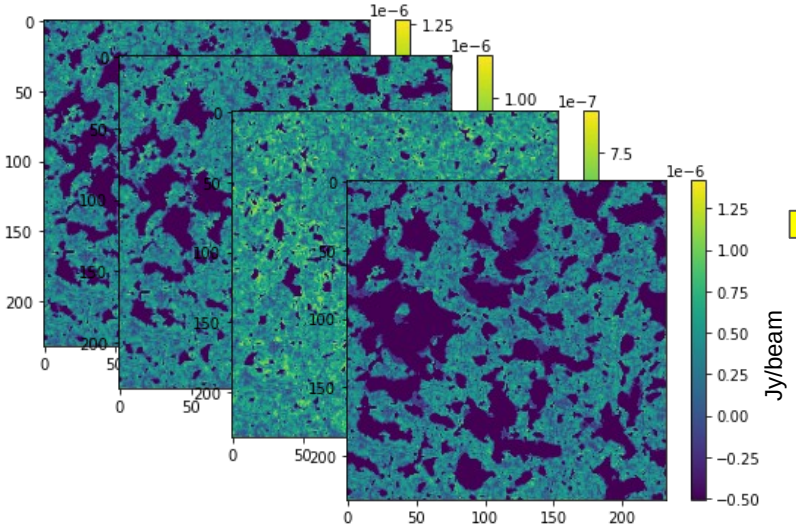
- Power spectrum analysis - Spherical averaged PS follows signal power if sources are displaced by > 0.5 arcsec, greater error lead to higher amplitude of residual power wrt signal power.





Mazumder et al. 2022

Training Data sets



Signal (21cmFAST)

Parameters Ranges

R_{mfp} = 10 Mpc to 60 Mpc

ζ = 10 to 60

T_{vir} = 4.5 to 6.0

(H.Shimabukuro et al. 2017)

Telescope Model (SKA1_Low)

21cmE2E pipeline

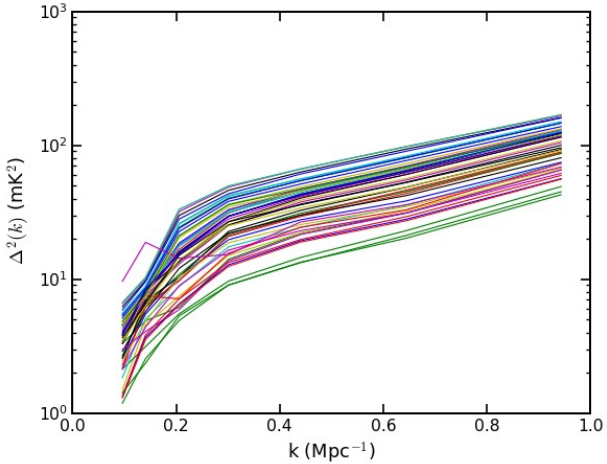


Fig : 300 datasets of the HI Power spectrums for the training.

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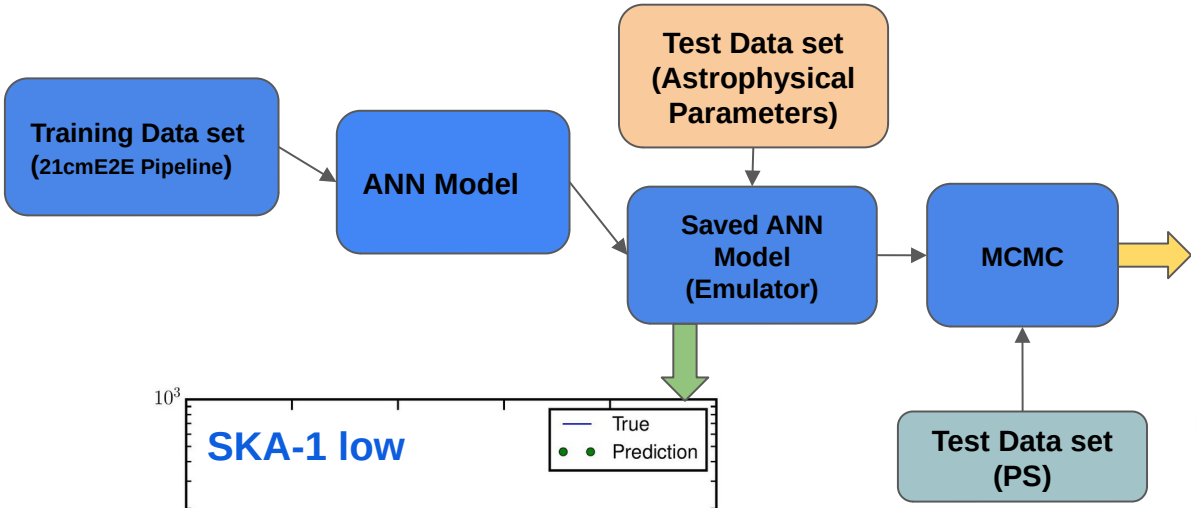
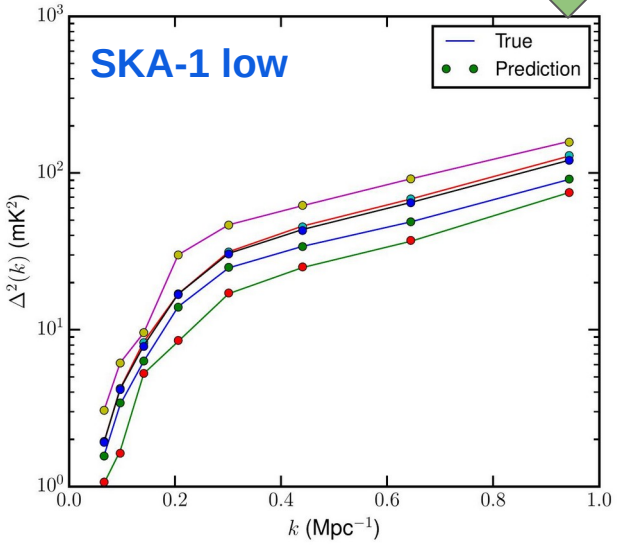
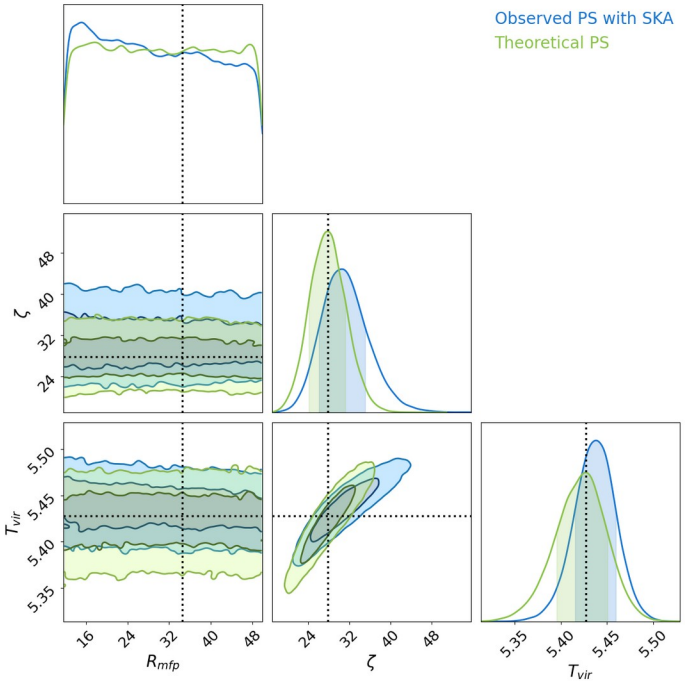
Emulating Power Spectrum and Parameter Extraction







Parameters	True Value	Observed PS with SKA1 low (MCMC)
R_{mfp}	34.67	–
ζ	27.92	$31.6^{+5.2}_{-4.0}$
T_{vir}	5.428	$5.439^{+0.021}_{-0.021}$

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MCMC Prediction for different Astrophysical Conditions

	Parameters	True Value	Observed PS with SKA1 low (MCMC)
PS1	R_{mfp}	34.67	–
	ζ	27.92	$31.6^{+5.2}_{-4.0}$
	T_{vir}	5.428	$5.439^{+0.021}_{-0.021}$
PS2	R_{mfp}	12.2	$20.0^{+14.1}_{-8.2}$
	ζ	18.42	$20.0^{+4.9}_{-3.9}$
	T_{vir}	4.738	$4.764^{+0.034}_{-0.047}$
PS3	R_{mfp}	44.33	–
	ζ	57.42	$59.8^{+0.0}_{-9.3}$
	T_{vir}	5.928	$5.926^{+0.013}_{-0.013}$

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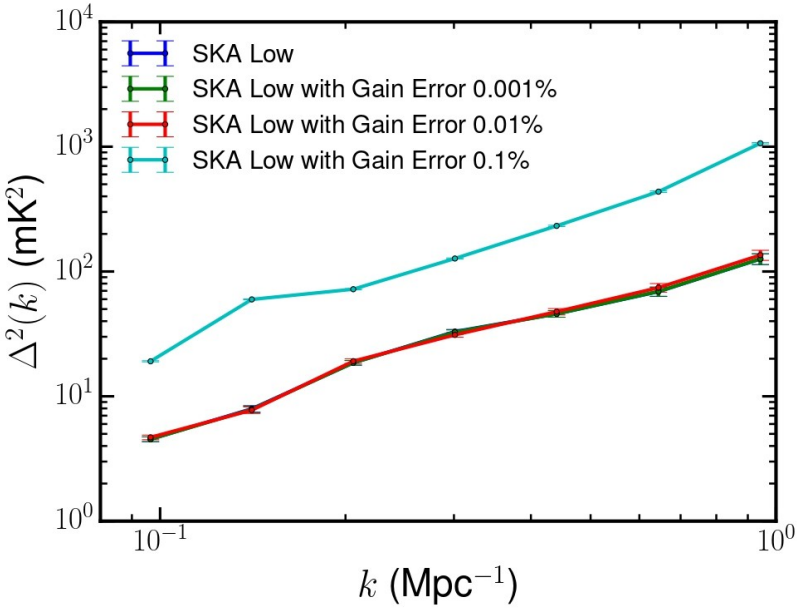
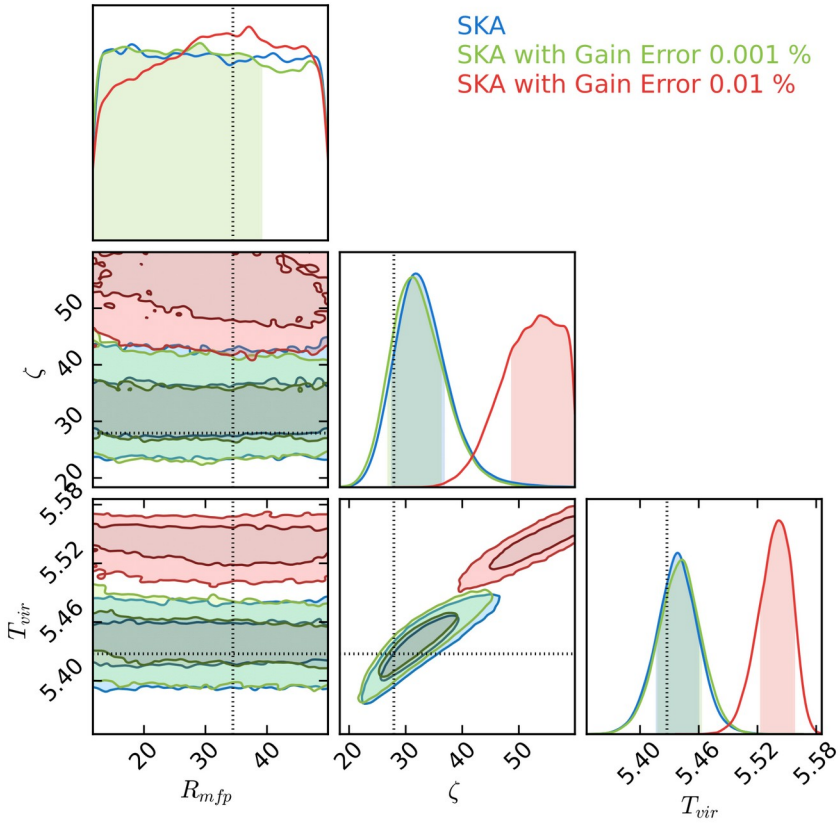
- In all cases, the ANN-based MCMC model's inferred ionizing efficiency ($\boldsymbol{\zeta}$) and T_{vir} closely match true values, but R_{mfp} is highly degenerate.
- Indicates model robustness for further study of calibrated Gain error and position error.

SKA1-Low with Gain Calibration Error





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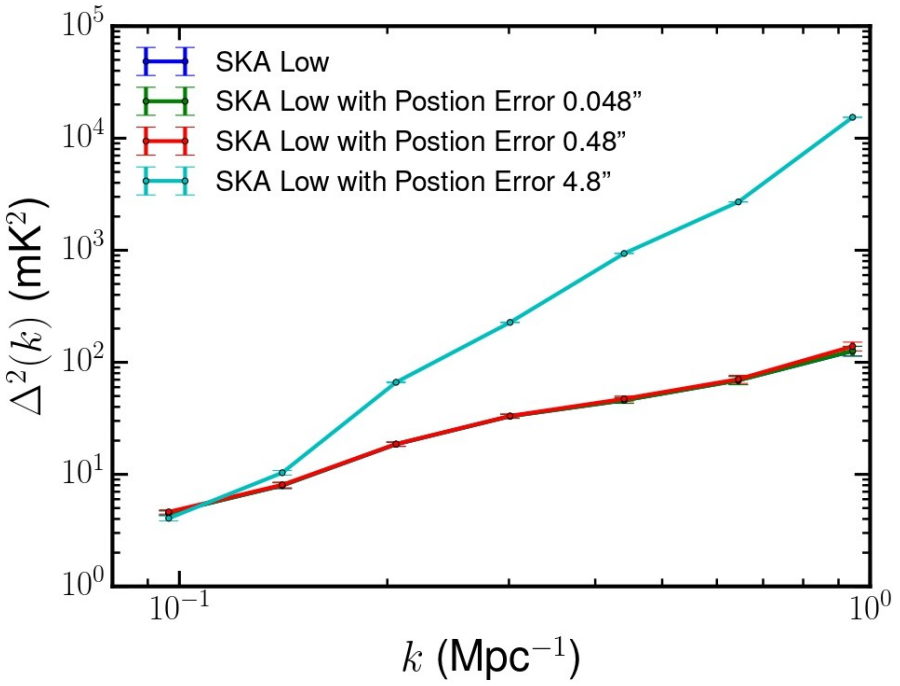
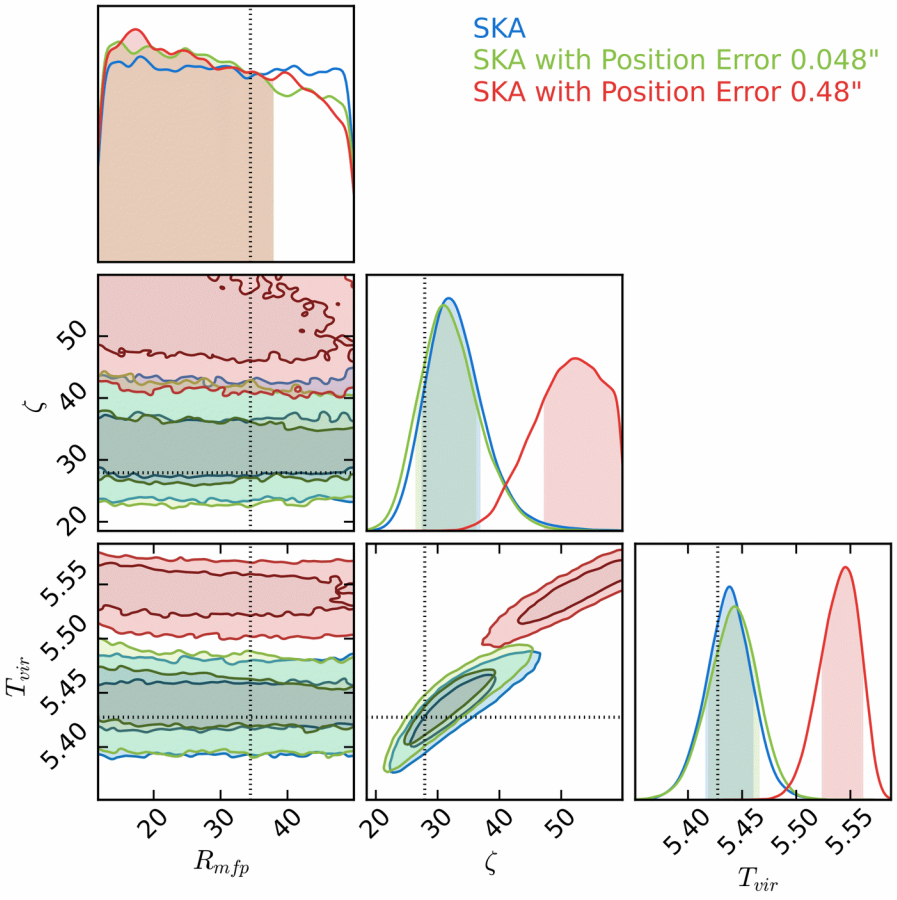
SKA1-Low with Position Error





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Summary/Future Work

GLOBAL 21 CM SIGNAL EXTRACTION

- ANN signal extraction is robust against slowly varying Ionosphere.
- Future work to include more dynamic ionosphere along with chromatic telescope beam.

21CM FLUCTUATIONS - POWER SPECTRA

- If the gain error exceeds 0.001% for interferometer, our derived astrophysical parameters will be biased due to the presence of gain error.
- Position errors exceeding 0.05 arcsec will bias the astrophysical parameters.
- This pipeline can be extended to study effects of chromatic primary beam, radio frequency interferences, foregrounds with spectral features.

Thank you